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U.S. Navy Coordinate Measuring Machines: A Study of Needs

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*Sponsored by the Navy Manufacturing Technology Program

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This report presents the results of a one year study of coordinate measuring machine technology at U.S. Navy manufacturing facilities, both in-house and contractor. This study has been funded by the Navy Manufacturing Technology (ManTech) Program in conjunction with the NIST Automated Manufacturing Research Facility (AMRF) Program. All members of the study team are technical staff members of the NIST Manufacturing Engineering Laboratory.

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The study team would also like to acknowledge and thank Production Technologies, Inc., for providing information regarding the ManTech contact persons at the facilities visited during this study.

References to commercial products and/or companies in this report are solely included for the purposes of this study. Such references do not indicate any endorsement or evaluation by NIST, the U.S. Navy, or any of the members of this study team.

EXECUTIVE SUMMARY

The National Institute of Standards and Technology (NIST) was commissioned by the U.S. Navy Manufacturing Technology (ManTech) Program to conduct a study of coordinate measuring machine (CMM) technology in the Navy. Specifically, the study has been conducted during fiscal year 1993 by members of the Precision Engineering Division and the Factory Automation Systems Division at NIST who are specialists in various aspects of the field of dimensional metrology. This report presents the results of this study.

The Navy ManTech Program has previously recognized that the functions associated with test and inspection processes in the production of Navy weapon systems are major contributing factors in the Navy's overall manufacturing costs. Based upon this recognition, as well as the recognition of the common presence of CMMs in the Navy, this study has been conducted to specifically examine the use of CMMs with respect to weapon system manufacture. The results of this study are an analysis of the state-of-the-practice in the Navy regarding CMM utilization. The results are also an analysis of the Navy's needs in CMM technologies. This study is intended to provide information that can be used to improve CMM efficiency throughout the Navy.

Conduct of the Study

The primary means of gathering information regarding Navy CMM usage, and dimensional inspection practices in general, was through a series of site visits to Navy manufacturing facilities. These site visits were conducted by combinations of the four NIST team members, usually two team members per visit. The visits included manufacturing facilities at both Navy base installations, which are termed in-house facilities throughout this report, and private industry contractors for Navy weapon systems. Twenty-two visits in all were conducted, consisting of visits to fifteen in-house facilities and seven contractor facilities.

The facilities visited were selected to represent a wide range of manufacturing and support operations associated with a broad cross section of Navy weapon systems, including fielded systems and systems under development. Operations were observed during the study that occurred in environments that ranged from low to high volume production, to repair and rework, to research and development, to testing and standards laboratories.

The study team developed a survey questionnaire that was used as an interview guide during the site visits. The questionnaire was used as a means of comprehensively discussing a predetermined set of issues at each facility, and as a means of assuring that similar topics were discussed at all facilities. The results of the survey questionnaire as completed by the team members for the facilities are included in this report.

The combination of team member technical expertise, the observations from the site visits, and

the results of the survey were used to develop a set of high priority issues for the Navy to consider regarding the improvement of CMM technology associated with Navy weapon system production and support.

Observations, Results, and Issues

Eighteen of the twenty-two facilities visited use CMMs in their operations; every contractor facility visited uses CMMs. The levels of sophistication of use of the observed CMMs varied greatly at the different facilities. For example, CMMs were being used at certain facilities in manual modes for quick, low-accuracy measurements of parts and fixtures; in semi-automatic modes with computer assistance for higher accuracy measurements of parts and tools; and in automatic modes under direct computer control (DCC) in controlled environments for even higher accuracy measurements of parts, gages and reference standards. DCC operation of CMMs at a few facilities was even occurring in networked computer engineering environments.

In general, the level of sophistication of CMM use at contractor facilities is much higher than at in-house facilities. The reason or reasons for this weren't completely revealed through the study, but apparently a great deal has to do with a particular facility's knowledge regarding, and perception of, a CMM. Contractor facilities, as observed, are more knowledgeable than in-house facilities about the ways in which a CMM can add value to a manufacturing process. In turn, the use of CMMs at contractor facilities was not only more sophisticated than in-house CMM use, but contractor levels of CMM use also better matched the particular measurement applications than at in-house facilities.

The sizes and complexities of measurement applications for Navy weapon systems are as diverse as the weapon systems themselves. This diversity of measurement application requirements was observed at virtually every facility visited. Each facility experiences its own unique problems and needs with respect to its own specific operations. However, several problems, needs, and areas of opportunity for improvement regarding the utilization of CMM technology were observed at many facilities. As such, this study found specific problems and needs at facilities that relate to specific processes and programs. Also, this study found a number of trends in CMMs that exist at several facilities.

The study identified a number of issues relating to the use of CMM technology in support of Navy weapon system production that are of high priority for consideration. The issues identified are relevant at several facilities, in-house and contractor, and the issues are relevant to several Navy weapon system programs. These issues represent means by which real and tangible improvements can be made in the use of CMMs in support of weapon system production.

The following is the list of issues that were determined by this study to be of high priority for Navy consideration. This list is not necessarily in prioritized order.

- CMMs in an integrated manufacturing environment
- Improved throughput for CMMs
- Education in CMM technology
- Large scale coordinate metrology
- Interim testing of CMMs
- The calibration of CMMs
- Capital equipment procurement
- CMM software and operating system enhancement
- Inspection strategies and planning
- Environmental/thermal effects on CMMs
- Training in CMM technology

The eleven issues above deal with concerns relating to CMMs at several levels. The majority of these issues relate to specific CMM technologies for which applied research and development work needs to be performed, such as improved throughput for CMMs, inspection strategies and planning, and CMMs in an integrated manufacturing environment. The list of issues also includes technologies for which a more basic, fundamental type of research must be performed, such as environmental/thermal effects on CMMs. In addition, the issue list includes the need for a dissemination of available CMM knowledge at both general and specific levels, such as education in CMM technology and training in CMM technology. The list also includes some broader, programmatic issues relating to CMMs, such as capital equipment procurement.

All the listed issues are explained in detail in the text of this report. The explanations of the issues provide summaries of the issues, as well as suggestions regarding what should be done to address the issues.

The eleven issues documented in this report are the keys to the improvement of CMM technology in the Navy. These issues represent areas that are both problematic for the Navy in the present, and should be addressed in the short term future in order to improve the Navy's overall manufacturing quality assurance practices and processes associated with its weapon systems.

CMMs are today's premier technology for dimensional quality assurance in Navy weapon system production. CMMs are flexible inspection systems that can be effectively and efficiently used in several environments associated with manufacturing and the support of manufacturing, ranging from research and development, to production, to standards laboratory work. CMMs are not simply overhead. CMMs can and do add value to manufacturing systems.

This report documents a study of Navy needs in CMM technologies that can and should be used for informational purposes, for planning purposes for future investments in weapon system technologies, and for programmatic purposes for the Navy ManTech program regarding the analysis of both present and future technological thrusts.

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I. INTRODUCTION

In 1992 the Department of Defense (DoD) Manufacturing Technology (ManTech) program prepared a plan for Congress that attempted to define the role and direction of ManTech within Defense procurement [1]. This plan was to also serve as the overall framework for both DoD- and Service-level future investments in manufacturing technology. One area that was identified in this plan as representing a major cost driver and an area needing ManTech development was test & inspection.

The National Institute of Standards and Technology (NIST) was commissioned by the U.S. Navy Manufacturing Technology (ManTech) Program during fiscal year 1993 (FY93) to conduct a comprehensive study of Navy needs regarding dimensional inspection. Specifically, this study was to focus on the area of coordinate measuring machine (CMM) technologies in Navy manufacturing. The study was conducted by staff members of the NIST Manufacturing Engineering Laboratory in conjunction with the Navy ManTech-funded Automated Manufacturing Research Facility (AMRF) at NIST. The study team consisted of recognized experts in hardware, software, and programmatic issues regarding dimensional metrology. The following report presents and summarizes the results of this study.

The mission of the study team was to conduct a survey of the CMM technology being used today by the Navy in the manufacture of Navy weapon systems. This survey included both in-house Navy base facilities, and Navy contractor facilities. These facilities covered an array of manufacturing processes associated with a cross-section of weapon systems. The study approach will be explained in detail in a later section of this report. A primary objective of the study was to determine and document both the state-of-the-art and the state-of-the-practice for Navy CMM technology. The data and other information gathered during the study is documented in this report for the general informative benefit of the Navy. This information can be used to determine Navy needs and areas of opportunity for improvement regarding CMM technology. The report also makes recommendations to the Navy as to what can and should be done to improve those areas related to CMMs where there is potential for improvement.

Why Study CMM Technologies?

Why should the Navy be concerned with a class of equipment that is not capable of producing a part when the emphasis in Defense manufacturing today is placed on increasing production and quality while decreasing cost? The answer is fairly simple. Virtually every manufacturing process requires a certain amount of inspection and/or monitoring to assure the control and the quality of the process. Coordinate metrology is not the only kind of dimensional measurement used in industry and the CMM is not the only kind of instrument in use. The use of CMMs does, however, represent one of the most vital—if not *the* most vital—quality assurance practices today.

In the current manufacturing world, there are more than 360 different models of CMMs available originating from nearly two dozen CMM makers [2]. The Navy needs CMMs as quality control tools for the manufacturing and measuring processes being conducted in the production of weapon systems.

Definitively stated, CMM technology is pervasively used and needed by the Navy in the support of weapon system manufacture. It must be made clear, however, that CMM technologies are generally the most sophisticated and frequently the most expensive quality control tools available. Because of the relative sophistication of CMM technologies, Navy manufacturers frequently find themselves in situations where the CMMs they have are either underutilized or improperly utilized. Another frequent situation in Navy manufacturing is the lack of CMMs where there is a real need. According to recent industrial research, about 75 percent of all CMMs sold in the world are underutilized [3]. What's worse is that 35 percent of all CMMs sold are collecting dust – simply not being used [3]. This seems to be true regarding the CMMs used in the manufacturing and measurement applications of the Navy.

Overview of CMM Technologies

A CMM is a measuring instrument that is used to assess whether the geometric dimensions of a manufactured discrete part conform to design specifications. This use also applies to assemblies and sub-assemblies. In addition, CMMs can be used for reverse engineering applications, or as calibration instruments to measure gages and physical reference artifacts.

Several illustrations of typical CMM configurations are shown in Figure 1 [4].

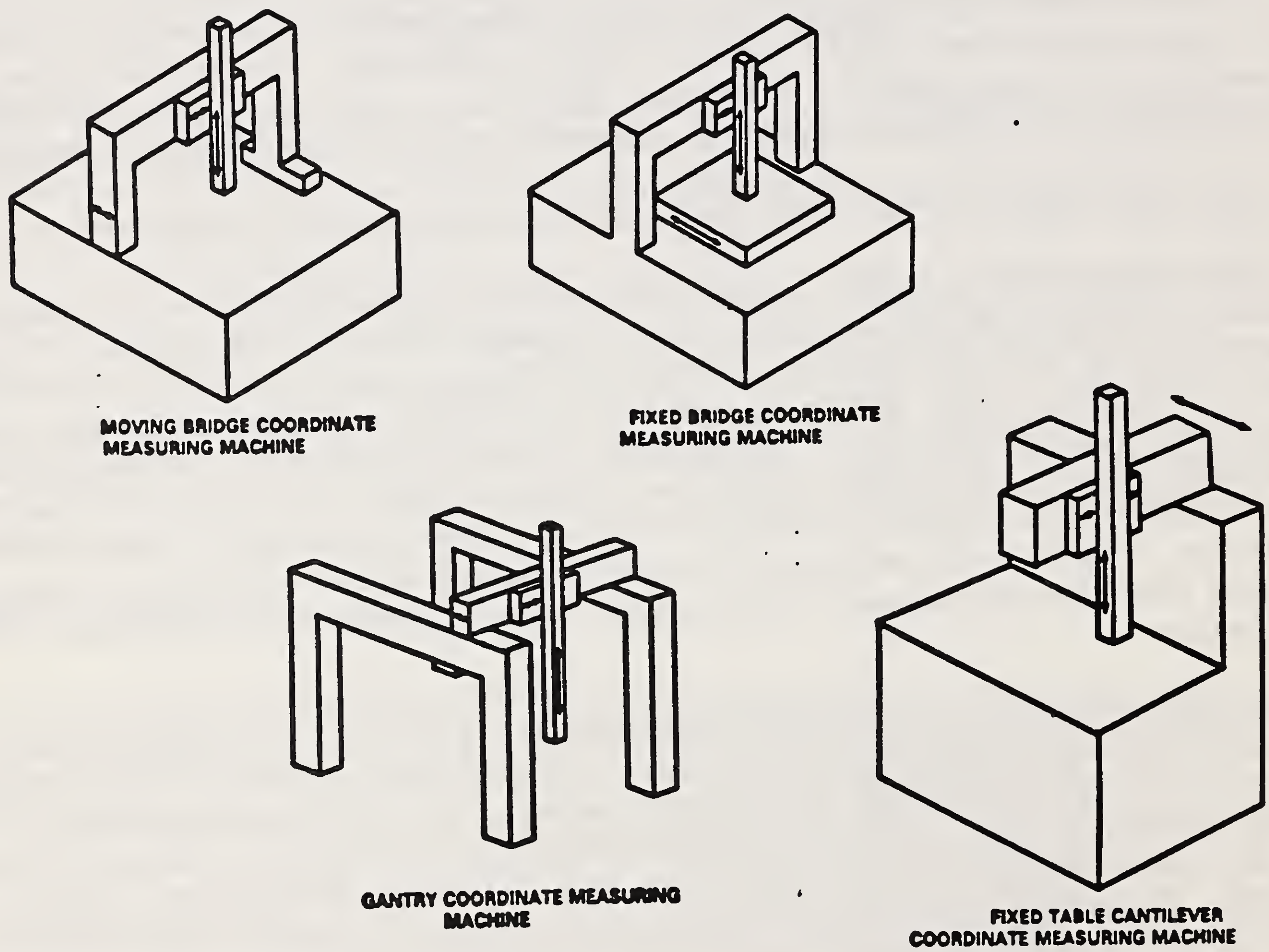
CMMs operate in three modes: manual, with an operator physically moving the machine through an inspection; semi-automatic, with the machine executing movements and data collection under joystick control; or automatic, under direct computer control (DCC). CMMs that are capable of DCC modes of operation are generally the most sophisticated, and accordingly the most expensive. These machines, however, also offer the most measurement flexibility, speed, and accuracy capabilities. DCC machines are capable of making measurements in an unmanned environment based upon the execution of prescribed computer programs. CMMs offer the real potential to greatly improve inspection capabilities, to increase output from existing equipment and personnel, and also to reduce costs associated with inspection.

Referring to Figure 1, a typical CMM operates through the collection of data from a part in a known three-dimensional measuring volume. A part is placed on the work table in the measuring volume of the CMM, and the part is measured in one, two, or three dimensions. Data collected from the part represents digitized part geometry that can be analyzed to give various characteristics of the geometry of that part. Geometric characterization of a part includes the determination of entities such as size, roundness, location in space, flatness, circularity, cylindricity, conicity, distance between two points, distance between a point and

a line, distance between a point and a plane, parallelism, straightness, angularity, profile, and perpendicularity, among others.

Data points are collected on a CMM by probing the part. The probing can occur either through contact or non-contact methods. Probing involves collecting the coordinate positions of pre-determined points on the part in order to characterize and assess the quality of the part. The probe is physically located on the machine at the end of the measuring ram. The position of the probe when a data point is collected is defined by the scales on the machine. These scales indicate where the probe is located within its measuring volume when the data collection, or part probing, is activated. When probing is activated, a signal is sent through the CMM's microelectronics to read the scales to determine the position of the probe. The machine is then capable, through software algorithms, of reporting the required information about the data collected. An example of typical reported information for a measurement might be the location of the center of a circle on a part, and the diameter of that circle based upon the collection of three or more data points located around the perimeter of the circle.

Figure 1
Illustration of Typical CMM Configurations



A few reasons why CMMs might be considered for integration into manufacturing and/or inspection processes follow [5]. This list is in no particular order of priority, yet each issue applies to Navy weapon system production.

- High speed production to high standards of precision make it difficult for many quality control functions to handle the increased demand for inspection throughput.
- Machined parts are becoming increasingly complex, with more measurement features and tighter tolerances.
- Traditional gaging techniques, such as the use of surface plates and height gages, are too slow, and, therefore, can be costly.
- Traditional gaging techniques are not capable of measuring to the accuracies required by part tolerances.
- Re-work operations require the reproduction of parts which have no available information regarding geometric characteristics; hence, these parts must be reverse engineered.
- Inspection information must be integrated into manufacturing process control operations to improve efficiency and output quality.
- The ability to interface CAD programming into inspection processes presents the opportunity to increase both inspection efficiency and overall process productivity.

Focus of This Study

The team set out to analyze the Navy's operations associated with the quality assessment of weapon system production. A CMM is capable of high-speed, high-precision, and high-flexibility inspection. While this is a fact, it must be stated that a CMM is not the answer to every organization's every measurement need. A CMM is a tool that offers great potential to improve manufacturing quality assurance. A comprehensive assessment of quality in a manufacturing-related operation implies the consideration of diverse issues [6], and not just whether a CMM is being used for inspection processes.

Not every measurement application requires the services of a CMM. The manufacturing associated with Navy weapon systems involves the production of parts that are both mission- and safety-critical. For such parts, there must be little doubt regarding the assessment of quality. It is imperative for these parts that the tools and processes used to determine quality be the optimum tools and processes available.

A primary objective of the manufacturing in the Navy, both in-house and contractor, is to produce better parts in a cheaper and faster manner for Navy weapon systems. Quality control in manufacturing is the foundation upon which this can occur, and CMMs are useful and vital tools for controlling quality. For purposes of this study, manufacturing quality is mainly determined by the level of dimensional conformity of manufactured parts to specified tolerances. The results, conclusions, and recommendations in the study reflect the level of confidence to which the Navy achieve's manufacturing quality in weapon system production.

II. STUDY APPROACH/METHODOLOGY

This study of Navy CMM needs was conducted using the following approach. A series of site visits was performed by the study team to cover a cross-section of Navy dimensional measurement interests throughout the life cycles of weapon system. Our visits covered a wide range of diverse Navy facilities associated with manufacturing and measurement, including research and development facilities, production facilities, standards and testing laboratories, and maintenance and re-work facilities (see Table 1). The visits were conducted to both in-house Navy facilities and to a diverse selection of Navy weapon systems commercial contractors (see Table 2). A representation of the geographical distribution of the sites visited, both in-house and contractor, is depicted in Figure 2.

Figure 2
Geographic Distribution of Facilities Visited

The study team developed a questionnaire related to dimensional metrology issues that was used as an informal "interview guide" during the site visits. The site visits were generally conducted with discussions among the team members and the facility hosts, and the questionnaire was a good topical guide for issues to be discussed at each facility. After each visit, the team members completed the questionnaire for the facility.

This survey questionnaire was neither developed nor used with the intent of providing a statistically sound data set upon which to base conclusions and recommendations. The survey questionnaire was intended to document some general trends relating to CMM technologies that exist at the visited facilities. The survey questionnaire provided a means of ensuring that the study team was thorough in addressing all the issues relevant to the study mission. The questionnaire and the aggregate result summaries from the twenty-two facilities visited are attached to this report as Appendix B.

Our hosts were clearly informed that the charge of the study team was to collect information on both the state-of-the-art and state-of-the-practice for CMM technology in the Navy. It was made clear at each visit that the team was not conducting a technical or administrative audit of the facilities. The intent of the visits, our hosts were told, was to collect and document information relating to the Navy's use of CMM technology. This information would be compiled in a report for the ManTech program that would facilitate the correlation of research in CMMs to the specific needs of the Navy at specific facilities. In other words, it was made clear that the main purpose of the study and the visits was to assist these facilities in the implementation and/or improvement of CMMs as measuring instruments used in support of Navy weapon systems. It was the study team's mission in conducting this study to document real Navy needs relating to CMMs.

A sample of the topics discussed during site visits and included in the questionnaires follows:

- Facility/company profile
- Facility/company products and/or services
- Dimensional sizes and shapes of parts measured
- Tolerance requirements and standards
- Types of dimensional measuring equipment used
- Equipment calibration, interim testing, and SPC employed
- Measurement environments
- Discrete point sampling strategies
- Computer aided inspection software used
- Mathematics used for dimensional and tolerance verification
- How measurement data is used within the mission of the facility

TABLE 1
Navy In-House Facilities Visited

Facility	Location	Operations Conducted	Weapon Systems	Contacts
Carderock Division Naval Surface Warfare Center	Annapolis, MD	Ship propulsion system R&D	Propellers for surface & sub-surface vessels	Tom Daugherty, Jim Preston, F. Rodriquez
Carderock Division Naval Surface Warfare Center	Bethesda, MD	Ship propulsion system R&D	Propellers for surface & sub-surface vessels	Kevin Lynaugh
Carderock Division Naval Surface Warfare Center	White Oak, MD	Ordnance and munitions R&D and maintenance	Shipboard guns (5"-16"), torpedoes (MK48), mines, munitions	Bill Deaton
Carderock Division Naval Surface Warfare Center	Dahlgren, VA	Ordnance and munitions R&D and maintenance	Shipboard guns (5"-16"), torpedoes (MK48), mines, munitions	Bill Deaton
Carderock Division Naval Surface Warfare Center	Philadelphia, PA	Ship propulsion system R&D and contractor technical monitoring	Surface and sub-surface vessels (incl. Seawolf)–mainly marine gearing	Mike Buvet Joe DeLuccia
Long Beach Naval Shipyard	Long Beach, CA	Ship maintenance, re-work, and repair	U.S. Pacific Fleet when in drydock	Dick Kimble Ignacio Delgadillo
Norfolk Naval Shipyard	Portsmouth, VA	Ship maintenance, re-work, and repair	U.S. Atlantic Fleet when in drydock	Don Martin
Puget Sound Naval Shipyard	Bremerton, WA	Ship maintenance, re-work, and repair	U.S. Pacific Fleet when in drydock	Gary Lutz Greg Wilhelm
Naval Systems and Sciences Laboratory	Seal Beach, CA	Evaluation & testing of the performance, readiness, reliability, and effectiveness of weapon systems	Trident, Poseidon, Polaris, Tomahawk, Subroc, Asroc, Terrier, Talos, Astor	Stanley Nakama Kirk Dugan
Naval Air Warfare Center Aircraft Division	Indianapolis, IN	Design, manufacture, and re-work of aviation missiles	Air-to-Air and Air-to-Ground missiles	Carlos Miller Chris Lang
Naval Warfare Assessment Center	Corona, CA	Engineering support for Navy service-wide calibration systems	All weapon systems supported by DoD Combined Calibrations Group	Jerry McGrath Pete Strucker
Naval Warfare Assessment Center	Pomona, CA	Physical & dimensional Type II standards laboratory	U.S. Pacific Fleet; Polaris ICBM	Ken Harrell
Naval Air Station Naval Aviation Depot	Pensacola, FL	Helicopter maintenance, re-work, and repair	Navy helicopter propulsion, including H60, H53E&D, H3	Jim Krippes

Facility	Location	Operations Conducted	Weapon Systems	Contacts
Naval Air Station Naval Aviation Depot	Norfolk, VA	Navy Primary Standards Lab-Eastern; maintenance, re-work, and repair of jet airframes and lading gear	U.S. Atlantic Fleet; F-14, F-4, A-4, A-6	Larry Divers
Naval Aviation Depot	Cherry Point, NC	Maintenance, re-work, and repair of helicopter engines	Marine Corps and Navy helicopters	Lewis Bridges

TABLE 2
Navy Contractor Facilities Visited

Facility	Location	Operations Conducted	Weapon Systems	Hosts
Martin Marietta Energy Systems Y-12 Plant	Oak Ridge, TN	Design and manufacture of propellers	Seawolf submarine prototype	Sam Murphy Sam McSpadden
McDonnell Douglas	St. Louis, MO	Design and manufacture of aircraft airframes	F/A-18, T-45, AV-8, C-5	Bill Gray Jim Bobelak
General Dynamics Land Systems	Warrenton, MI	Design and manufacture of wheeled (or track) vehicles	Advanced Amphibious Assault Vehicle (presently bidding for contract award)	Michael Puzzoli William Dittmer
Bell Helicopter Textron	Fort Worth, TX	Design and manufacture of helicopters	H1W Cobra and V-22 Osprey	Frank Schoenthal Daniel McIlroy
Lockheed Aeronautical Systems	Marietta, GA	Design and manufacture of aircraft	P-3 and C-130	Jim Jones Frank Denney, Jr.
Westinghouse Electric Marine Division	Sunnyvale, CA	Missile launch and ship propulsion systems	Trident missile launch systems; surface & sub-surface vessel propulsion (gearing) systems	Richard Walker Bill Taylor
Texas Instruments	Dallas, TX	Design and manufacture of missile airframes and electronics	DoD Joint Standoff Weapon	Dennis Coston Keith Campbell

Each facility visit was conducted during one day. The visits generally consisted of some introductory discussion between the study team and the hosts, followed by a tour of the facility, then concluding with some additional parting and summarizing discussions.

None of the visits were conducted with the emphasis on programmatic issues, which was by study team design. The visits were generally arranged through the facility's designated ManTech point of contact over the telephone, or through some other prior acquaintance of the study team. As such, our hosts were typically scientists, engineers, or department managers who deal with the technology issues we were discussing on a daily basis. The primary intent of the site visits was to gather information relating to CMM technologies, and this was accomplished with each visit.

III. STUDY RESULTS AND OBSERVATIONS

Facility Visits

The study team conducted twenty-two site visits to Navy facilities around the country. Fifteen in-house facilities and seven (prime) weapon system contractor facilities were visited. The facility visits represent a broad cross-section of manufacturing and weapon system support operations conducted by the Navy. The associated Navy weapon systems for these facilities also represent a broad cross-section of weapon systems used by the Navy today, including ships, submarines, airplanes, helicopters, missiles, guns, torpedoes, munitions and ordnance, and amphibious vehicles.

The facility visits were summarized in trip reports written by each member of the study team that conducted each particular visit. These trip reports were condensed into one or two paragraph highlights, which are attached to this report in Appendix A. The study team will maintain on file the complete reports for future reference.

Dimensional Inspection Survey

The questionnaire used to survey the dimensional inspection capabilities of the visited Navy facilities is contained in Appendix B. Appendix B also includes the results of all the surveys completed by the study team members. It should be noted again that the surveys were completed by the study team after the visits were made. The questionnaire was not produced with the intent of compiling scientifically and statistically sound data upon which to base conclusions and recommendations. The questionnaire was, however, intended to be used for the purpose of maintaining a topical focus on dimensional inspection and CMMs during the site visits. It was also intended to capture some general trends that are occurring at the facilities relating to these topics.

The survey results indicate several interesting issues relating to Navy inspection and manufacturing practices. Explanations and/or interpretations of the survey results follow. It should be noted that the survey results are actually the compiled number of responses that each item received when the study team members completed the questionnaires.

Concerning facility/company profile, the survey results indicate that the facilities visited in this study primarily conduct manufacturing-related operations associated with Navy aerospace and marine weapon systems. Facilities that represented Navy concerns in automotive and electronics products were also visited.

The nature of operations observed represented a wide cross section of manufacturing-related activities performed by the Navy. These activities range from production as a Navy supplier, to job-shop activities associated with re-work, to job-shop and specialty shop activities associated with research, to operations of dedicated metrology and inspection laboratories in

support of an array of manufacturing processes.

The types of parts with which the facilities are concerned are mainly sized in the millimeter to meter range, and include virtually every type of geometric feature. While there were several facilities working with tolerances in the micrometer range, the majority of tolerances observed were in the ten micrometer to several millimeter range. The application of ANSI Y14.5-defined geometric tolerances [7] was observed at some sites; however, not all the facilities use this standard in their tolerancing practices. Apparently, military standard requirement provide the majority of the guidelines used for tolerancing.

It was discovered that CMMs are widespread in Navy weapon system production. Of the 22 facilities visited, it was found that 18 use CMMs in some capacity for inspection. Further, the survey showed that 13 of these 18 facilities conduct CMM inspections in the direct computer controlled (DCC) mode, which is the most sophisticated form of CMM operation. **Every contractor facility** visited was not only using CMMs, but was using CMMs in DCC mode.

In addition to CMMs, we observed a wide variety of other manual and computer-assisted dimensional inspection equipment, including height gages, micrometers, calipers, special thread gages, various mechanical comparators, linear measuring machines, optical comparators, and special vision-based systems. Manual dimensional equipment was more prevalent at the in-house facilities. Contractors generally had more modern facilities and measuring equipment.

The survey questionnaire included a number of other questions not directly concerning the above issues. Several of these questions relate to measurement uncertainty, which is described below.

Measurement Uncertainty

A measurement using a CMM produces a result that is an approximation. This is true of any measurement, even the most accurate and precise one. The usefulness of measurement results is to a large extent determined by the quality of the measurement's statement of uncertainty. The statement of uncertainty quantifies the level of measurement approximation. A measurement result is incomplete without a quantitative statement of its uncertainty.[8]

In order to define and quantify uncertainty in measurements, the elements that introduce uncertainty into a measurement process should be monitored. These elements can in turn be controlled to reduce measurement uncertainty. The primary components of measurement uncertainty are random and systematic errors in the measurement process. The definition and quantification of these random and systematic errors constitute the error budget of a measurement process.

A statement of measurement uncertainty is vital to the usefulness of any measurement system. For example, one could not verify the dimensions of a part with tolerances of 2.5 micrometers

if the total uncertainty of the measurement process used for verification as determined by a quantified error budget was 5 micrometers. The results would have no meaning.

The concept of measurement uncertainty is not well understood in the world of Navy manufacturing. This lack of understanding, which exists in both in-house and contractor measurement practices, became apparent during the study team's visits to the various facilities. In several instances, especially at the in-house facilities, the demonstrated level of understanding was close to zero.

CMM Trends and Observations

Regarding the integration of CMM technologies into the overall manufacturing processes for Navy weapon systems, the following observations can be made from this study.

The most prominent observation taken from this study is that sophistication of CMM usage at contractor facilities far exceeds that which resides at in-house facilities. The reason for this did not become very clear during the study. This was not a function of the production of mission- and safety-critical parts, as both contractor and in-house facilities are responsible for these parts. This was not a function of part application, as both contractors and in-house facilities were producing parts being applied directly into assemblies and sub-assemblies for weapon systems. Both types of facilities were also producing inventory parts to be used as spare or replacement elements in weapon systems. Moreover, this was not a function of part tolerance, as both types of facilities were producing both tightly toleranced as well as looser toleranced parts.

The difference in the level of sophistication of CMM usage between contractor and in-house facilities is an observation that merits further investigation. A point to consider is that contractor facilities are conducting their operations in the execution of **contracts**. The execution of these contracts is driven in part by the bottom line—costs.

The amount of general knowledge regarding CMMs was much higher at contractor facilities than at in-house facilities. Some in-house facilities were conducting complex manufacturing to tight tolerances without familiarity of CMMs. Some in-house facilities had CMMs that were either being under-utilized, or not utilized at all. Most in-house facilities using CMMs were not using them as efficiently as they could have been.

Several instances were noted where the CMM(s) being used at a facility was not the best type for the measurement application(s). Often the capability of the CMM did not meet the requirement of the inspection application. Sometimes the CMM being used had capabilities exceeding the measurement requirements of the parts. Some of these observations also applied to contractor facilities; however, they were much more prevalent at the in-house facilities.

Regarding data collection and programming, contact probing was the most common form of CMM data collection. Several facilities were using both touch trigger and scanning probes.

There was also a fairly high percentage of facilities using CAD systems in their operations (almost 70% of the facilities visited). These CAD systems, however, were not generally integrated into inspection processes.

Other Observations

It was noted at the majority of in-house facilities visited that inspection functions performed in support of the overall mission of the facility were generally viewed as non-value added activities. Inspection was an overhead function from an accounting perspective that was frequently targeted for cost cutting in the forms of staff or budget (both operating and capital) reductions. An underlying concern at virtually every in-house facility studied was a recent or a pending budget reduction. There was very little emphasis being placed upon actually improving processes.

This observation can be summarized through an anecdote from one of the facilities. In an effort to reduce overhead, post-process inspection for a particular product with a direct, safety-critical application in a Navy ship was completely eliminated. When it was questioned how this move affected the quality of the manufacturing operations, the response (while somewhat tongue in cheek) was that now the reject rate was zero. If they didn't inspect a product, they couldn't reject it.

A rather curious observation should be noted regarding the comparison of dimensional metrology capabilities versus other test and inspection capabilities at the visited facilities. At most in-house and contractor facilities the study team observed very sophisticated levels of test and inspection capabilities for purposes other than dimensional, such as electrical and physical. These capabilities were generally far superior to the capabilities in dimensional, especially at the in-house facilities. The reason for this was not apparant and merits further investigation.

Additional specific observations from the study will be included in Section IV of this report, and will appear as recommendations and conclusions.

IV. ISSUES AND RECOMMENDATIONS

CMM Issues for Consideration

This section documents this study team's recommendations for the Navy to consider regarding the use of CMM technology in the production of weapon systems. The recommendations here are based upon a combination of the information gathered during the study through the site visits and the individual and collective expertise of this study team in the field of dimensional metrology.

To begin this section of recommendations, it is first necessary to give a brief listing of the CMM technology issues determined by the study team to be worthy of Navy consideration. These issues are found in Table 3 and represent both problems and opportunities for improvement for CMM issues relating to Navy weapon systems production.

The information included in Table 3 is not listed in order of priority. Each issue listed, however, was determined to be of **high** priority by the study team for Navy consideration. The items listed in Table 3 are all issues that were found to be relevant at several facilities and represent the potential for achievable benefits throughout the Navy. The issues in Table 3 would require between one and three years to correct or improve, as estimated by the study team.

It is not intended that every issue listed in this section should be the responsibility of the Navy ManTech program. It is outside the scope of this report to make the managerial decisions on behalf of the Navy as to which agency/organization is responsible for addressing these issues. It is possible that in several, if not all, instances a combination of one or more organizations that should be primarily concerned with resolving the issues, since these organizations would stand to benefit most from the resolution of the issue.

Table 3 is organized to present each issue with an array of additional information relevant to the issue. This additional information includes the facilities that would benefit from improvement of the issue. A contact is given for each applicable facility, which also identifies the host of the study team visit. A listing of the weapon systems that would benefit from the issue resolution or improvement is provided in the "Relevant Weapon Systems" column of the table. Finally, Table 3 includes a brief description of the potential solution to each identified issue, along with relevant benefits to be derived.

It should be noted that Table 3 does not contain information regarding the Navy "stakeholder" for each issue, assuming that a stakeholder is defined as a champion at the decision making level for funding. This study did not place the study team in contact with those people that would be considered stakeholders. The study focused on CMM technology as it is being used by and for the Navy in weapon systems production. This meant the goal of the facility visits was to discover the real technology issues at the shop floor and laboratory

levels. This approach was quite successful in revealing a variety of issues that are both areas where the Navy could benefit through improvement, as well as real problems.

TABLE 3
Identified CMM Issues

CMM Issue	Applicable Facility	Facility Contact	Relevant Weapon Systems	Potential Solution and/or Benefit
CMMs in an Integrated Mfg. Environment	•CDNSWC White Oak & Dahlgren •Lockheed •Texas Instruments	•B. Deaton, CDNSWC •J. Jones, Lockheed •D. Coston, TI	•Mk48 torpedo, Navy mines •Ordnance & munitions •P-3, C-130 •JSOW	Concurrent engineering environment that reduces programming time & enhances analysis capability
Improved Throughput for CMMs	•NADEP, Cherry Pt. •Lockheed •McDonnell Douglas •Texas Instruments •Bell •Martin Marietta	•L. Bridges, NADEP Cherry Pt. •J. Jones, Lockheed •D. Coston, TI •D. McIlroy, Bell •S. Murphy, Martin Marietta	•USMC helicopters •P-3, C-130 •T-45, F/A-18, AV-8 •JSOW •V22 Osprey •Seawolf Submarine	Increased CMM productivity; reduced time required for measurement; increased measurement flexibility
Management Awareness in CMM Technology	•NAVSEA Directorate •NAVAIR Directorate •All in-house facilities visited	•D. Martin, Norfolk Shipyard •I. Delgadillo & D. Kimble , Long Beach Shipyard	All systems observed in this study and all those falling within the scope of the listed Directorates involving mfg.	Education at levels where decisions are made on funding & procurement; knowledge provision regarding use & benefits of CMMs
Large Scale Coordinate Metrology	•Martin Marietta •CDNSWC, Bethesda •Norfolk Naval Shipyard •Long Beach Naval Shipyard •McDonnell Douglas •Lockheed	•S. Murphy, Martin Marietta •K. Lynaugh, CDNSWC Bethesda •D. Martin, Norfolk Shipyard •D. Kimble, Long Beach Shipyard •J. Bobelak, McDonnell Douglas •J. Jones, Lockheed	•Seawolf submarine •Marine propellers •General Navy shipbuilding •U.S. Atlantic Fleet •U.S. Pacific Fleet •T-45, F/A-18, AV-8 •P-3, C-130	New technology development will allow precision "CMM-like" measurements to be applied where not previously possible, such as assembled ship structure, propulsor systems, and airframes
Interim Testing for CMMs	•NWAC,Corona & Pomona •NADEP, Pensacola •NAWACAD, Indianapolis	•B. Downing, NWAC Corona •K. Harrell, NWAC Pomona •J. Krippes, NADEP Pensacola •L. Halbig, Indianapolis	•U.S. Pacific Fleet •Polaris ICBM •H60, H53E&D, H3 helicopters •Air-to-air & air-to-surface missiles	Provision of means for periodically checking CMMs to ensure measurement reliability & reduce uncertainty
The Calibration of CMMs	Each facility, contractor & in-house, presently using or planning the use of CMMs	n/a	Each weapon system observed in this study & mentioned in this report, and all other weapon systems involving discrete part manufacturing	Provision of a standard, usable procedure for CMM calibration to indicate uncertainties for individual measurements
Capital Equipment Procurement	Each facility, contractor & in-house, presently using or planning the use of CMMs	n/a	Each weapon system observed in this study & mentioned in this report, and all other weapon systems involving discrete part manufacturing	Consultation assistance provided to optimally correlate Navy measurement applications with equipment procurement
CMM Software and Operating System Enhancement	•Texas Instruments •Westinghouse Electric •Puget Sound Shipyard	•D. Coston, TI •B. Taylor & R. Walker, Westinghouse Electric •G. Wilhelm, Puget Sound Shipyard	•JSOW •Surface and sub-surface marine propulsion systems •U.S. Pacific Fleet	Development of advanced algorithms for tolerance verification; reduction of overall measurement uncertainty
Inspection Strategies and Planning	•McDonnell Douglas •Texas Instruments •Westinghouse Electric •Puget Sound Shipyard •NADEP Pensacola •NAWCAD Indianapolis •Martin Marietta	•J. Bobelak, McDonnell Douglas •D. Coston, TI •B. Taylor & R. Walker, Westinghouse Electric •G. Wilhelm, Puget Sound Shipyard •J. Krippes, NADEP Pensacola •L. Halbig, Indianapolis •S. Murphy, Martin Marietta	•T-45, F/A-18, AV-8 •JSOW •Surface and sub-surface marine propulsion systems •U.S. Pacific Fleet •H60, H53E&D, H3 helicopters •Air-to-air & air-to-surface missiles •Seawolf submarine	Compilation of recommended sampling and programming strategies into "handbook" format for specific geometric features based upon various data collection methods

CMM Issue	Applicable Facility	Facility Contact	Relevant Weapon Systems	Potential Solution and/or Benefit
Environmental/ Thermal Effects on CMMs	•Puget Sound Shipyard •NADEP Pensacola •NAWCAD Indianapolis	•G. Wilhelm, Puget Sound Shipyard •J. Krippes, NADEP Pensacola •L. Halbig, Indianapolis	•U.S. Pacific Fleet •H60, H53E&D, H3 helicopters •Air-to-air and air-to-surface missiles	Increased understanding of CMM and part deformations due to environmental variations and development of compensation for these can potentially increase inspection precision by orders of magnitude
Training in CMM Technology	•Seal Beach •NADEP Norfolk •Norfolk Shipyard •Long Beach Shipyard •CDNSWC Annapolis	•S. Nakama, Seal Beach •L. Divers, NADEP Norfolk •D. Martin, Norfolk Shipyard •I. Delgadillo, Long Beach Shipyard •T. Daugherty, CDNSWC Annapolis	•Trident, Polaris, Subroc, Asroc, Tomahawk, Poseidon •F-14, F-4, A-4, A-6 •U.S. Atlantic Fleet •U.S. Pacific Fleet •Surface and sub-surface marine propellers	CMM training to users that will ensure optimum performance and efficiency of CMMs, with the incorporation of training in basic metrology principals and applications

TABLE 4
Potential Navy Stakeholders

CMM Issue	Applicable Navy Command/Directorate
CMMs in an Integrated Manufacturing Environment	NAVSEA, NAVAIR
Improved Throughput for CMMs	NAVAIR, NAVSEA
Education in CMM Technology	NAVSEA, NAVAIR, ONR, et.al.
Large Scale Coordinate Metrology	NAVSEA, NAVAIR
Interim Testing for CMMs	NAVSEA, NAVAIR
The Calibration of CMMs	NAVSEA, NAVAIR
Capital Equipment Procurement	Supply Offices working w/DLA, NAVSEA, NAVAIR
CMM Software & Operating System Enhancement	NAVSEA, ONR
Inspection Strategies & Planning	NAVAIR, NAVSEA
Environmental/Thermal Effects on CMMs	NAVSEA, NAVAIR, ONR
Training in CMM Technology	NAVSEA, NAVAIR

Individual Issue Description and Recommendations

CMMs in an Integrated Manufacturing Environment

The weapon system production world of today is placing increasing emphasis upon the creation of more integrated manufacturing environments. Such environments extensively employ the concepts of concurrent engineering, giving all elements of the overall manufacturing process access to and a share of the information and concerns of each individual process. This access is gained through an integrated manufacturing resource environment that typically includes CAD representations of parts; component, sub-assembly, and assembly drawings and designs; CNC programs for specific machining processes; shop floor machining and/or assembly sequences; scheduling information; tooling and fixturing data; and any relevant safety issues.

Such an integrated manufacturing environment is not complete unless it includes the information relevant for part inspection. In order to close the manufacturing process loop, quality control processes must be included in the environment. As such, the inclusion of programming capabilities of DCC CMMs in such an environment is integral to achieving a complete concurrent, integrated manufacturing environment. Inspection integration would optimize operations: by reducing inspection programming time, reducing overall time for inspection, promoting "design for inspectability," and enhancing in-process and post-process analysis capabilities.

Improved Throughput for CMMs

Typical manufacturing CMMs utilize mechanical touch-trigger probing for the collection of inspection data for all types of geometric features. Such probing techniques are ideally suited for certain inspection applications involving relatively simple geometries, but they can be time-consuming for others. This time consumption generally increases as both complexity of geometry and required levels of accuracy increase.

Other data collection devices, such as vision systems, structured light surface measurement systems, and other non-contact probing systems can collect relatively large quantities of data in short periods of time at useful accuracies. These data collection devices are being integrated for use on CMMs, but the technologies are still developing in most cases. Such devices, for example, often lack inspection access to certain types of geometries, such as ordinary holes.

Many inspection applications for Navy weapon systems involve complex surfaces and high accuracies; hence, there is the need to collect many data points efficiently and comprehensively. The development and integration of alternative coordinate measuring technology and methodology is required by several Navy weapon system programs to optimize the combination of CMM throughput with inspection flexibility and accuracy. Such work may require the development of a new generation of machine controller.

Education in CMM Technology

CMM technology is about twenty years old. CMM technology, however, is frequently misunderstood, even by those people who routinely use CMMs for inspection purposes. CMMs are not simply instruments of manufacturing overhead. CMMs are not only valuable for processes involving repeated measurements. The most accurate CMM is not always the best CMM. The most sophisticated CMM is not always the best CMM. CMMs are not only used for post-process verification in manufacturing. The measurements produced by a CMM are not always the "right" answers.

The truths contained in the above statements regarding CMMs are not well-known in the Navy. The majority of CMMs observed that were actually being used were generally operated by seemingly conscientious inspectors. The issue is much broader than teaching an inspector how to make a CMM touch a part to collect data. The pervasive problem regarding CMM knowledge was a general lack of understanding regarding how to best apply the use of a CMM to a particular manufacturing-related application.

Large Scale Coordinate Metrology

Navy weapon system production routinely involves the assembly of piece parts into sub-assemblies and system assemblies, as well as the assembly of sub-assemblies into system assemblies. These sub-assemblies and system assemblies, especially common in shipbuilding and aircraft production, are often too large to allow the application of precise CMM inspection. Alternative means of large scale inspection are often inadequate due to a lack of precision or other constraints, such as the ability to produce an economically viable measurement, or requirements for unbroken lines of sight for certain optical methods. According to one in-house facility visited, the lack of good large scale dimensional metrology for shipbuilding causes naval construction costs to be sixteen percent higher than necessary (see Appendix A, page A-1). The development of viable new technologies that will allow the application of "CMM-like" precision measurements where not previously possible in a large scale range is vital to Navy weapon system production, as observed during this study.

The dimensional accuracy of many large parts and assemblies, particularly those on aircraft and missiles, are critical to the performance of the weapon systems. As an example, variations in large airframe parts can result in the use of numerous shims during assembly, increasing the weight of the plane. There are a number of new and evolving measurement methods for large parts, but there have been no comprehensive studies of the metrology of these systems.

Since the parts and assemblies of concern are large and must be measured on the shop floor or in an assembly area, the error sources are much larger compared to those encountered in the metrology lab or CMM inspection area. The most promising new methods of large scale metrology are optical, including theodolite-based triangulation, photogrammetry, and structured light with computer vision.

Large parts also have substantial thermal expansion coefficients. Inspection is severely limited by the thermal and optical environments in all of the large scale measurement systems. To use new technologies reliably, a number of parameters must be studied. Among these parameters are the effects of temperature gradients in the measurement environment, the effects of vibration on measurements, the effects of air pressure variations, requirements for part surface preparation, and the optimization of measurement procedures such as beam geometry, target placement, and viewing angle. The development of adequate environmental monitoring and optimized procedures to control the effects of these error sources is critical to the success of these measurement methods in the production of Navy weapon systems.

Interim Testing for CMMs

Users of CMMs need efficient and user-friendly means by which the measurement reliability of a CMM can be periodically checked or certified in a relatively small amount of time. This is the key to maintaining a comprehensive system of statistical process control (SPC) for CMMs. This can occur through the advanced development of interim test artifacts and procedures for CMMs that are quick and easy to use. Such interim tests can be conducted once a week, or even once a day, and should require thirty minutes or less to run.

Interim testing can be used to develop measurement assurance programs and SPC for CMM measurements that assist in the reduction of measurement uncertainty. Interim testing is a quick means of periodically conducting a modified "calibration" of a CMM between scheduled complete CMM calibrations. This study observed a need for improved interim testing capabilities throughout the Navy, and heard requests from several facilities for assistance in the development of this technology.

The Calibration of CMMs

Most facilities observed in the study that are using CMMs calibrate their machines at some regular interval, usually about once per year. There exists, however, no standardized procedure to properly calibrate a CMM. The ASME/B89.1.12 standard, "Performance Evaluation of Coordinate Measuring Machines," [5] gives a recommended procedure for the acceptance testing of a CMM. This standard is not intended to provide a repeated calibration procedure for a CMM. Currently, CMM calibrations consist of shortened versions of the B89.1.12 procedure; or modifications, or sometimes replications, of the German DIN standard [9]; or measurements of some physical object as a measurement reference, usually similar to the part being produced and measured; or the recommended calibration procedures of the manufacturer of the specific machine. While some of these methods may be adequate in certain circumstances, several procedures were grossly inadequate. There needs to be an accepted definition of what the calibration of a CMM means, along with the procedures by which a machine can be properly calibrated for its specific measurement applications.

Perhaps the most important problem with calibration procedures today is that none of the procedures give the users the most important aspect of a calibration. The user of a CMM

must know what the expected and actual uncertainties are for the measurement of an actual part on the CMM. Current CMM calibration procedures provide information that the performance of a machine is within certain limits. Although such general information is useful, the accuracy of an individual measurement can often be much greater than the overall accuracy of the machine. This is a function of the uncertainty of a measurement. Any measurement, including one produced on a CMM, is only an estimate of some physical value. The statement of uncertainty for a measurement assigns a confidence level to the estimate of the particular value being measured. CMM calibrations will only be comprehensive when they produce information regarding measurement uncertainty.

Calibration procedures and associated software must be developed that will take measured values from a CMM and compute the uncertainty of those values as a function of the measurement conditions. These uncertainty-related measurement conditions include part size, location of the part in the CMM measuring volume where the measurement occurs, the number of repeated measurements, types of features being measured, and environmental conditions. Such procedures and software are not presently available on even the most sophisticated CMMs being used in support of Navy weapon system production.

Capital Equipment Procurement

A CMM can be a useful, economical inspection tool in a job shop environment or in a high volume production environment or in a standards laboratory environment. Not every measurement application associated with Navy weapon system production requires the use of a CMM. Not every Navy weapon system CMM measurement application requires the use of a sophisticated, high accuracy, expensive, DCC CMM. A manufacturing or standards laboratory measurement requiring verification of design tolerances in the 2.5 micrometers range generally cannot be made with ordinary, manual hard gaging instruments. The inspection of the three-dimensional surface of a large surface ship propeller blade does not require the same instrument as the inspection of the hatch cover for the ship's engine room, yet both of these parts are in the same weapon system. The measurement requirements of a primary standards laboratory are not the same as the measurement requirement of a depot re-work center, or a ship research center.

The stated issues are examples of technical items that require an in-depth knowledge of dimensional and coordinate metrology to best optimize the selection of measuring equipment for particular measurement applications. Implied here is the need to identify measurement needs, secondary uses for equipment, and similar applications at various facilities. Procurement specifications should be written by or in consultation with knowledgeable experts to make the most efficient use of weapon system funds. This unfortunately rarely occurs, as was observed during this study.

CMM Software and Operating System Enhancement

When assessing the dimensional quality of a manufactured part, an ultimate goal is to

determine the degree to which part dimensions conform to design specifications. Moreover, the value of any dimensional measurement is determined by the degree of uncertainty associated with the results produced by the measurement process. This study observed a pervasive lack of consideration for measurement uncertainty in Navy manufacturing. The common practice, especially when using CMMs, was to make a measurement of a part and assign that measurement as the resultant deviation of the part's dimensions from specifications. This was done consistently without consideration for the elements of the measurement process that produce uncertainty. Too many cases were witnessed where measurements were producing results that had very little analytical value. Several approaches to solving this Navy quality assurance problem can and should be taken.

One element of measurement uncertainty involves the software and operating systems of CMMs. When a set of data points is collected by a CMM through probing a part, the tolerance verification software of the CMM processes the points and reports whether the measured part is within design specifications. The CMM software uses implemented mathematical algorithms; consequently, the algorithms determine the capability of CMM software. From the observations of this study and the results of the survey, currently available CMMs typically only provide least-square approximations of fitting substitute features to sample data points. This approximation from software algorithms contributes to the uncertainty of the measurement results. These algorithms can not accurately verify parts specified in national standard geometric tolerances, such as those that are commonly used in Navy weapon system production.[7],[10]

Knowledgeable users usually disable CMM software functions when verifying part geometric tolerances due to the inadequacy of common software. For example, part data is often collected and output by a CMM as raw data points representing locations in the CMM measuring volume. These points are then taken to some third party software program for geometric analysis. It is necessary to improve typical software capabilities by developing advanced fitting and data analysis algorithms for CMMs. Specifically, advanced algorithms must be developed for geometric tolerance verification and fitting sculptured curves and surfaces from measured coordinates of manufactured parts. More mathematically sound algorithms are urgently needed by Navy facilities and industry. Soft functional gaging capability is also needed to increase the utility of CMMs as inspection tools.

Inspection Strategies and Planning

A common problem associated with the measurement of parts to assess the degree of their conformity to desired dimensional specifications involves the determination of how and where to measure the part to assess it. As a basic example, how many points should be collected around a circle and how should those points be spaced to best determine the location of the center of that circle and the circle's diameter? A DCC CMM has default algorithms to handle these questions for basic geometric features, but these defaults don't always produce the best data collection scenarios for every application. Measurement applications, especially those in the Navy using CMMs, often involve complex data collection to ultimately determine a part's

dimensional quality. Design for inspectability and inspection planning are concepts that have not yet been integrated into Navy weapon system production.

When using CMMs to make measurements, different inspection strategies can result in different measured values. A typical CMM inspection strategy includes the determination of the locations and number of points to measure, the selection of probes, the determination of machine measuring and positioning speeds, and the proper fixturing of the piece. Inspection guidelines must be made available to Navy facilities and contractors using CMMs. Well documented and optimized inspection strategies for particular weapon system applications are critical for ensuring inspection validity and minimizing inspection costs.

Inspection strategies and planning should be developed to assist the Navy inspector in collecting data for making measurements that best reflect the size, form, and figure of a part, not a rounded-off estimate of these entities. These strategies need to be compiled into some means that can be easily disseminated and used throughout the Navy.

Environmental/Thermal Effects on CMMs

Measurements made with CMMs are dependent on the environment in which they occur. This fact is recognized by MIL-STD 45662A, section 5.3, [10] in its requirement that calibrations be made at, or when applicable corrected to, acceptable environmental conditions. The environmental conditions that affect CMM measurements include, but are not limited to, temperature, barometric pressure, humidity, vibration, and cleanliness. Temperature is the environmental parameter which most frequently affects dimensional measurements; both the part and CMM are affected. The temperature effect is especially important for large parts (wings, struts, helicopter rotors or submarine propeller blades) or large CMMs - the error in a measurement due to a non-standard uniform temperature (not 20°C), is directly proportional to length. If the temperature of the part or CMM is uniform, measurements can be corrected for the linear expansion or contraction of the part or CMM given their temperature and material make-up.

The case of non-uniform or changing temperature, however, remains problematic. In this case the shape, not just the size, of the CMM or part is affected. Spatial gradients in the temperature of a machine or part may lead to seemingly disproportionate dimensional errors due to bending effects (analogous to a bi-metallic effect). These temperature gradients may result from environmental changes or heat sources internal to the CMM. Presently, no commercially available CMM has the capability to make measurements of a part with undegraded accuracy when that CMM or part is at a non-uniform temperature. Facilities and techniques for acquiring detailed temperature distributions of both the part and CMM, as well as the ability to integrate this information in a corrective model, are lacking in the current state-of-the-art. In many cases the ability to fully compensate for thermal effects on CMMs and parts could substantially reduce measurement uncertainty.

For the special case in which CMMs use lasers for scales, the environmental conditions are also

important. The index of refraction of the air in the path of the laser must be known in order to relate interferometric measurements to length. The index of refraction is a function, primarily, of the temperature, humidity and barometric pressure of the air. Thus, these environmental parameters must be measured in order to convert an interferometric measurement to a length measurement.

Environmental effects on CMM measurements occur in both shop floor and standards laboratory environments. The understanding of these effects must exist for large and small variations from standard, uniform conditions to accommodate the needs of the Navy.

Training in CMM Technology -- Bridging the State-of-the-Art and the State-of-the-Practice

This study observed substantial differences in the degrees of sophistication of CMM knowledge, practice, and awareness throughout the Navy. The general level of sophistication regarding CMMs observed at in-house facilities was less than at contractor facilities. Also, the variability of sophistication observed was larger at in-house than at contractor facilities. The dimensional measurement staff of the Navy, especially at in-house facilities, needs to be closer to a state-of-the-art level of sophistication.

Many of the issues described in earlier sections of the report have components that can be addressed through education and training. With some additions, these include: 1. selection and use of the appropriate CMM for the appropriate measurement job – involving CMM type, class of accuracy, and computer control; 2. the impact of thermal and other environmental effects on measurements with CMMs; 3. the selection and use of available probing technologies – involving characteristic errors, advantages, and disadvantages; 4. the importance of part sampling strategies when making discrete measurements with CMMs; 5. the estimation of CMM measurement uncertainty, using error budget analysis; 6. the value and proper implementation of existing standards for the evaluation of CMM performance, especially the B-89 standard for acceptance testing; and 7. the value and incorporation of CAD systems into CMM programming and measurement analysis, especially using DMIS [11] and other standards.

As Navy installations down-size, close, and merge, there will be an increased need for basic training in the use of CMMs and metrology principals in order to maintain the skills and capability of Navy staff at levels necessary to support weapon system production. Multimedia, self-paced instruction could give management the flexibility to deal with today's rapidly changing Navy production, research, and repair environments.

V. SUMMARY AND CONCLUSIONS

Navy Weapon System Production Operations Observed

This study focused on the application of CMM technologies in facilities and operations associated with the support and production of Navy weapon systems. The Navy weapon systems observed in this study represent examples of world class technologies and manufacturing operations. Their use by the Navy has successfully defended this country for over two hundred years, and their existence is a tribute to our defense system. The production of these weapon systems, as with all leading edge technologies, must continuously be improved as our country prepares to enter the twenty-first century.

A study such as the one being summarized here can provoke many questions. Why has our Navy operated so successfully for as long as it has if so many flaws exist in weapon system production? Are the flaws in quality assurance processes *really* critical to weapon system safety and/or mission? Is there a financial incentive to implement quality assurance improvements associated with CMMs? Why should the Navy invest in CMM technologies in the face of increased pressure to cost weapon system production costs?

These and other questions are viable, and should be asked prior to investments in technology improvements. While it was not within the scope of this study to answer these questions directly, the objectives of this study were to provide documentation and information to be used by the Navy in attempting to answer such questions.

Continuous improvement in the quality of weapon system production is a real and tangible means by which the systems can continue to be produced into the next century at controllable costs to the Navy and in turn to the American taxpayer.

In global manufacturing today, the state-of-the-art in quality control instrumentation is flexible CMM technology. Levels of sophistication of CMM technology are extremely wide ranging, and the application of CMM technology can be optimized to be commensurate with virtually any measurement requirement for any particular manufacturing environment. This study discovered that the state-of-the-practice regarding CMM technologies used in support of Navy weapon system production is well below the available state-of-the-art. **More importantly, this study observed that the incorporation of CMM technologies into the support of Navy weapon system production demonstrates a strikingly low amount of optimization of available technology for specific applications.**

This study presents a collection of results and observations gathered by a team of metrology and CMM experts. As such, it must be remembered that the issues presented here represent areas of opportunity for the Navy to improve the support of weapon system production.

Summary of Results

Twenty-two facilities were visited in the conduct of this study. The facilities visited included fifteen Navy in-house installations and seven Navy contractor installations. All the contractors visited were weapon system primes. These facilities represented a wide cross-section of the types of organizations concerned with the production of a wide cross-section of Navy weapon systems. The demographics and other specifics regarding the facilities studied is contained in this report in Tables 1 and 2 and Figure 1.

The cross-section of facilities and weapon systems studied represents a comprehensive account of the manufacturing operations and processes typical of Navy weapon system production. Eighteen of the facilities visited had at least one CMM that was used in some way as an inspection instrument. Two of the remaining four facilities had CMMs that weren't being used at all, and the other two facilities had no CMMs. Every contractor facility visited is using CMMs in support of their manufacturing operations.

The facilities studied do not include all Navy facilities that conduct or support weapon system production; however, the facilities studied do account for over sixty CMMs owned directly by the Navy, or operating in support of Navy weapon systems. The number of CMMs supporting Navy weapon systems should be much larger as a means of improving quality assurance for weapon system production.

Summary of Navy CMM Issues

The primary CMM issues determined during this study as meriting the most consideration by the Navy for near term improvement and/or correction are summarized in Tables 3 and 4. These issues, in no specific order of importance, are listed here.

- CMMs in an integrated manufacturing environment
- Improved throughput for CMMs
- Education in CMM technology
- Large scale coordinate metrology
- Interim testing of CMMs
- The calibration of CMMs
- Capital equipment procurement
- CMM software & operating system enhancement
- Inspection strategies & planning
- Environmental/thermal effects on CMMs
- Training in CMM technology

Each of the listed issues has been determined by the study team as being of high priority. These determinations were based upon several reasons. These include each issue's potential for beneficial impact on weapon system manufacturing; the pervasiveness of each issue at several facilities throughout the Navy; and large gaps between the observed state-of-the-practice

in the Navy and the available state-of-the-art for several issues.

Each issue identified as being critical to the improvement of CMM technology in support of Navy weapon system production is also based upon several predications. These predications generally involve conceptual issues pertaining to CMMs, that include the following:

- A CMM is a flexible inspection tool.
- A CMM can be used in many measurement applications, ranging from manufacturing process control, to manufacturing process verification, to reverse engineering applications in rework and repair environments, to laboratory measurement of standard manufacturing reference materials.
- The level of sophistication of the use of a CMM should be correlated with the measurement application to optimize the use of the technology.
- The use of a CMM is not merely an overhead function. **The integration of reliable measurements into the quality control of a manufacturing process can and does add value to the process.**
- CMM technology is not next generation technology – it is the technology of today in manufacturing quality control.
- The dimensional integrity of manufactured parts is the cornerstone for the ability of parts to function and perform as designed for designed lifetimes, and it is the foundation for the interchangeability of parts.
- The CMM is the means by which Navy weapon system manufacturers and supporters can assure the dimensional integrity of the parts, components, and assemblies in weapon systems.

Conclusions

The levels of CMM technology being used throughout the Navy in support of weapon system manufacturing as observed by this study are strikingly different between Navy in-house and Navy contractor facilities. While no specific reason as to why this is so was apparant during the study, several hypotheses can be made. Rather than state a list of questionable rationalizations as heard at several facilities, it must be noted that contractors who are motivated by a bottom line profit margin have made the choice to invest in the use of CMM technology in support of manufacturing operations.

Navy contractor manufacturing operations involve a span of several types of CMM measuring applications, from high volume production process verification and control to high precision standards laboratory measurement. Navy in-house manufacturing operations span the same range of measurement applications. The CMM is a flexible inspection tool that can be used in any environment associated with Navy weapon system production as a valuable means of assuring manufacturing quality. Navy in-house facilities could learn a great deal from their contractor counterparts regarding the effective use of CMM technology in support of manufacturing operations.

This study and this report have presented a list of eleven critical issues for the Navy to consider regarding the use of CMM technologies in support of weapon system production. These issues represent real problems that are being experienced by the people in the Navy who are "in the trenches" on a daily basis and are responsible for specific manufacturing operations associated with Navy weapon system production. The issues represent real needs and real areas of opportunity for improvement "in the trenches" of Navy weapon system production. The issues also have all been conveyed to this study team as being **critical** to improving the quality assurance in Navy weapon system production.

CMMs as inspection tools are not the technology of tomorrow--they are the technology of today. The time is now for the Navy to bring the quality control processes of Navy weapon system production into the modern world. Now is the time for the Navy to follow the lead of its contractors and realize the benefits of CMM technologies in support of weapon system production, benefits that include cost savings.

Consideration of the information provided in this study will provide the tangible means by which the integration of CMM technology into Navy weapon system production can be improved. This improvement will in turn produce significant overall improvement of weapon system production.

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APPENDIX A

TRIP REPORT SUMMARIES

NAVY IN-HOUSE FACILITIES

David Taylor Ship Research Center
Carderock Division of the Naval Surface Warfare Center
Bethesda, MD

This center is a major facility for Navy ship design, research and development. Ship, submarine, and ordnance models are tested by instrumented towing in several basins. An inspection facility with several CMMs assure dimensional quality for discrete parts that are manufactured in-house, as well as for models. Here, the lack of good large-scale dimensional metrology for shipbuilding was identified as being responsible for naval construction costing sixteen percent more than necessary.

Carderock Division of the Naval Surface Warfare Center
Annapolis, MD

This facility is involved mainly in research work associated with propulsion systems on naval vessels. Accordingly, manufacturing operations consist of the production of propeller parts which are used in models by this and other Carderock facilities, including Bethesda. The manufacturing taking place here involves fairly complex five-axis machining, yet the processes have little quality assurance integrated into them. Inspection of machined parts, which are mostly aluminum, occurs at the production machine and is performed by the machine operator. Part tolerances are typically in the 25 micrometer range, with some applications in the 2.5 micrometer range. Based upon our visit, this facility may be producing parts this well on a regular basis; however, the inspection processes being employed are not capable of verifying processes at this level. The facility does have a Moore M48 high accuracy CMM, but it is not presently being used and is scheduled to be transferred to the Bethesda detachment. Machining capabilities here are sophisticated and are networked for programming through a central computer; the sophistication of inspection at the facility must be improved to at least be commensurate with the machining.

Naval Surface Warfare Centers
White Oak, MD and Dahlgren, VA

Ordnance research, development and testing are the primary missions of these centers. Their functions will be consolidated at the Dahlgren site within the next two years. Ordnance sub-components such as shells - and sub-systems such as trigger mechanisms for mines and torpedoes are designed here. Limited production runs serve as feedback for the research and development process and demonstrate manufacturability for transfer to mass production. Dimensional inspection by a competent metrology laboratory, which contains one manual CMM, serves to assure quality for safety and mission critical items. The laboratory also provides some feedback for the manufacturing operation. Firing cams are an example of a safety critical item inspected here. A substantial, forward-thinking effort to develop an integrated design engineering and manufacturing environment is underway. This environment does not currently include, but would benefit from, integration of dimensional inspection capability.

Carderock Division of the Naval Surface Warfare Center
Philadelphia, PA

This facility, which is located at the Philadelphia Naval Shipyard, is responsible primarily for assuring that the quality capabilities of contractors who deliver gear components and gearing systems to the Navy comply with specifications. This work has primarily involved the development and administration of a program for certifying the gear measuring machines used by contractors. The main inspection instrument used by the facility in this program is a Maag SP260 gear checking machine which measures master gears and artifacts which the Navy then uses at contractor facilities for results comparison purposes. The spirit of this program is to be commended; however, close examination of the details of the program reveal several areas to be improved. Included here are the metrology principles applied in the measurement of masters at Philadelphia. This involves improving calibration cycles of artifacts and integrating environmental controls into measurements to improve their uncertainties.

Naval Air Warfare Center Aircraft Division
Indianapolis, IN

The visit was a pleasant surprise after visiting so many Navy facilities where they have no concept of dimensional metrology. They have nine CMMs (six old Sheffields, two new Sheffields, and a new Zeiss). The machines are not in a temperature controlled room, however, the personnel are aware of degradation caused by the lack of good temperature control. They think they are doing better than they probably are as they really don't understand some of the more subtle errors caused by lack of temperature control. The CMMs

are part of production, which while generally not a good idea, probably is okay in this case as they have adopted the concept that production is responsible for quality, and that the responsibility of quality is to assist the production people. This is a new concept which I have seen only once before—at an HP facility in Santa Rosa California. The machine shop is clean with modern equipment. It is considerably ahead of most Navy facilities. I was told they had recently been audited by people from DLA as to their capabilities to do contract work for the Defense Logistic Agency. This seemed to be a great idea as now spare parts are ordered from the original equipment manufacturers who in turn often subcontract the work to foreign companies. They did not feel they had any serious problems with one exception. They think the software on the Zeiss does not measure correctly in accordance with the Y14 requirements. Because the system is closed, they are not able to find out what the Zeiss really does. They would like NIST help in solving some of these problems. While they did not ask for it, they are in need of interim testing and better calibration methods.

Naval Warfare Assessment Center
Pomona, CA

Pomona is a unique measurement facility in the Navy. There is located at Pomona both a Type II standards laboratory and, at the same facility, a gage laboratory for the measurement of functional gages which are used to check weapon systems. During our visit, they were checking a gage which is used to measure the straightness of a polaris missile tube. Because the two facilities have worked closely together, Pomona has one of the best equipped labs in the Navy. They have had a Leitz CMM for several years, but most of the time it was idle. Recently Ken Harrell has been using it, and he is interested in serving as a test site for the NIST interim testing devices. It would be in our mutual interest to maintain a close relationship to the Pomona facility.

Naval Warfare Assessment Center
Corona, CA

Corona provides the engineering support for all the Navy's calibration laboratories. They write standards and develop testing procedures. They also are in charge of the engineering design and testing of new equipment which is to be purchased by the testing laboratories. While there is a plan for them to absorb the Pomona facility, they currently are doing their work without access to laboratory facilities—at least this is true in the dimensional area. Perhaps because of this, their advise and recommendations are often ignored at the laboratories they serve. They would better serve the manufacturing needs of the Navy if they became more knowledgeable about manufacturing practices. There is a need for the Navy to integrate standards, inspection and manufacturing—or at least get them to talk to each other.

Naval Air Station Naval Aviation Depot
Pensacola, FL

The Precision Measurement Center at this facility is responsible for supporting NADEP operations through first article inspection programs for in-house and contractor part production, engineering investigations, calibrations, and select quality control inspections for in-house production. The facility is a well-equipped, well-run dimensional metrology laboratory that measures items associated with Navy helicopters. The primary measuring instrument is a Zeiss Hofler CMM used for gear measurements, but there are also several other state-of-the-art instruments here for a variety of dimensional measurements. This facility is presently working cooperatively with NIST in the investigation of the absolute measurement of screw threads, and has indicated a sincere desire to cooperate on additional measurement programs. The quality of this facility as compared to most Navy in-house inspection facilities is outstanding and should continue to be utilized to the fullest extent.

Long Beach Naval Shipyard
Long Beach, CA

Manufacturing operations at the shipyard are focused upon support of drydock operations for repair and overhaul for the pacific fleet. Accordingly, the machining capabilities here are fairly impressive, producing complex parts to be applied directly to ships in port with short lead times. The emphasis at the facility is placed upon using machinists' skills and pride to produce parts correctly, which generally seems to work. There is almost zero inspection of manufactured parts and the facility does not track parts once they are shipped. This means that they generally do not know whether parts fit into assemblies, function in assemblies, or operate without failure or wear for required life cycles. Dimensional metrology knowledge is almost non-existent here, which is definitely not an optimal situation, as parts are routinely required to be produced to tolerances in the 25 micrometer to 2.5 micrometer range. A proper integration of coordinate measuring technology at this facility seems long overdue.

Naval Weapons Station Naval Systems & Sciences Laboratory
Seal Beach, CA

This facility evaluates and tests the performance, readiness, reliability, and effectiveness of naval weapon systems. Its primary mission is the quality evaluation of weapon system stockpiles, quality verification of contractor's new products, such as first article testing, and providing recommendations for implementing stockpile improvement programs. The laboratory is well-equipped with a wide variety of sophisticated testing instruments which facilitate the quality execution of the lab's testing functions. The lab is also tasked with the conduct of dimensional analysis of parts in weapon systems which generally have tolerances

in the 2.5 micrometer range; however, the most sophisticated dimensional equipment here is a height gauge. This laboratory typifies the lack of understanding in the Navy regarding the importance of dimensional metrology to the quality production of a weapon system. The facility also represents an excellent opportunity to integrate high accuracy coordinate measuring technology for demonstration of the importance of dimensional integrity of parts as it relates to part performance.

Puget Sound Naval Shipyard
Bremerton, Washington

The shipyard maintains aircraft carriers, cruisers, and submarines. In the repair facility, machine tools and CMMs are used to machine and inspect parts. The CMMs are used to check the conformance of parts to specified tolerances. The parts are manufactured at the Shop or received from a contractor's delivery. The specified tolerances are geometric tolerances. The tolerances are as tight as 20 micrometers for the distance between two holes of a part. The geometric tolerances are used in conformance to ANSI Y14.5. The CMMs are sitting on the shop floors without shields from heat sources. Sun light and machine tool vibrations can easily affect measure parts and CMMs measurement processes. The ambient temperatures are measured when a CMM is in the operation of taking measurement. The records do show that the measurement results vary proportionally to temperature changes. The shop has machine tools to rework parts of ships or produce replacing parts for ships. The CMMs are used for both receiving parts from contractors and assuring parts manufactured at the Shop within specified tolerances. The repair shop is interested in a guideline for part surface sampling and technology for protection of CMMs from environmental effects, such as heat and vibration.

Norfolk Naval Shipyard
Portsmouth, VA

This facility conducts manufacturing operations associated with re-work and overhaul for ships in drydock at the base from the Atlantic Fleet. Our visit here took us to the Metrology Branch, which has the charge of being the shipyard's standards laboratory. The primary function of this branch in this role is to provide measurements of standard artifacts used by local labs in the calibration of instruments used by the machining shops in their quality control operations. The local labs had less dimensional capability than the primary lab, which was weak itself. The connection between the lab on the base with the best dimensional capabilities and the manufacturing operations at the base greatly needs to be improved. Manufacturing here, as is typical of most shipyards, consists of fairly complex machining with very little quality control in place, other than some in-process on machine hard gaging of parts by machinists. There was a significant amount of equipment at the base (in a local lab) for

the measurement of screw threads, yet it was unclear how this equipment was being utilized. Coordinate measuring technology could vastly improve not only the manufacturing quality control, but also the laboratory measurement capabilities here.

Naval Air Station Naval Aviation Depot
Norfolk, VA

Our visit was to the Standards Laboratory at this facility, which used to be a Navy Type II Laboratory, but is now the Navy's Eastern Primary Standards Laboratory, absorbing the responsibilities of the recently closed Type I lab at the Washington Navy Yard. The lab, while it does not have a CMM, does have a good array of dimensional equipment that allows it to function in the measurement of standards for other laboratories, both in-house and off-base. This lab knows virtually nothing about the manufacturing for which their calibrations provide support, which is reflected in a degradation of quality assurance as it cycles from the standards lab to the working lab to the shop floor. The production area had two CMMs, neither of which was functional, and generally had poor capabilities for dimensional inspection. This facility as it is presently structured cannot properly verify its production through dimensional inspection.

Naval Aviation Depot - Rework Facility
Cherry Point, North Carolina

The facility is a rework center that repairs turbine and compressor blades of jet engines used by Marine Corps jet airplanes and helicopters. This Depot is one of the six Naval Aviation Depots, and only this Depot supports Marine Corps aviation needs. Damaged blades go through a repairing process: welding, profiling, grounding, hand-finishing, and coating. After the blade rework process, the finished blades are visually inspected. Some kinds of blades are manually inspected using gages. Coordinate measuring machines with tactile probes have been considered. They have two major problems for the applications at the Depot: probes cannot reach all the features in a blade and touch probing is too slow. Therefore, it is too costly to use touch probing for reworked blades. The rework center is interested in non-contact measuring techniques. The rework center is also interested in measurement equipment to graphically display the comparison of the measurements with the nominal shape and accurately identify out-of-tolerance areas. They also are interest in integrating the measurement devices into the profiling and surface finishing processes to guide the profiling and finishing processes. Also of interest is the calibration of non-contact sensors and the measuring machines.

NAVY CONTRACTOR FACILITIES

McDonnell Douglas
St. Louis, MO

This facility is the Navy's prime contractor for the airframe production of the T-45 trainer plane, the F/A-18 fighter/attack plane, and the Marine Corps AV-8 vertical take-off and landing plane. Manufacturing operations here are supported by a dozen CMMs; we saw eight during our visit to the facility's Tooling Center and Machining Center metrology laboratory. The level of sophistication of use for these machines was higher in the Machining Center due to the requirement for higher accuracies, and the machines were generally used with the integration of fairly good metrology principles. Environmental control was employed, machines were certified (though incomplete) twice a year, and some SPC for machine probing was evident. A good scanning machine would improve inspection operations here, as would the correct integration of DMIS into CMM programming, due to the vast array of machines in use. Also, an inspection "handbook" would assist operations in the Tooling Center, where all CMM inspections are done manually and there is little logic applied to inspection planning.

Martin-Marietta Energy Systems
Y-12 Plant, Oak Ridge, TN

Propellers blanks for the Seawolf submarine program are machined, finished and assembled at the Y-12 plant. Four state-of-the art coordinate measuring machines are used to measure the blades in addition to the tooling used in the machining and finishing of the part. Continuous scanning or non-contact measurement of the propeller blades would provide a faster, spatially denser measurement of this highly complicated form. It would also provide feedback to assure the surface finish necessary to minimize cavitation and thus maximize blade lifetime.

General Dynamics - Land Systems Division
Warren, Michigan

The Land Systems Division of GD is in the process of bidding a contract for building advanced amphibious assault vehicle for the Marine Corps. The Division makes tanks (M1A1 and M1A2) and tank parts for the Army. Currently, the Division uses CAD systems for part design and a VSA (Variation Simulation Analysis) software package for analysis of specified dimensions and tolerances in designs. All CMMs in the facility are operated in manual modes. For part inspection, quality engineers decide how many points to sample on a part feature

surface. Then CMM operators manually bring the probe on a CMM to touch the part surface and take a specified number of sample points. CMM software is used for verifying whether the measured parts are within the tolerance specifications based on the sampled points. The quality program of GD is integrating statistical process control (SPC) technology into the manufacturing process to prevent errors on-line and at the machine centers to reduce defects and cost. The CMMs are in temperature controlled rooms and are used for checking manufactured parts to determine whether they conform to tolerance specifications. The tolerance specifications are in ANSI Y14.5 format. CMM operators determine where to take sample points on a surface by guessing possible locations of high contact points; however, sometimes, operators sample a surface using evenly distributed sample points. The quality program is interested in measurement equipment that can be integrated into manufacturing processed for in-process inspection to monitor process behavior. Such technology and methodology would help quality assurance personnel scientifically determine the sampling strategy using CMMs. It could provide the capability for designers to perform 3D tolerance analysis and synthesis to scientifically allocate tolerances, and it would include CMM software that could determine error sources of manufacturing processes.

Texas Instruments
Dallas, TX

Texas Instrument produces Joint Standoff Weapon (JSOW) systems for the Navy. The facility applies MIL-9858 to certify processes. There are vision machines, optical gaging systems and CMMs. For in-process control, touch-trigger probes and data analysis software are integrated into NC machine tools for measurement purposes. But, more capabilities are needed by this data analysis software for analyzing critical parameters of manufacturing processes. Automated Inspection is a program for coordinating the usage of coordinate measuring systems in the facility. The automated inspection program is interested in the following capabilities: a better way for in-process inspection to control manufacturing processes; more efficient and effective techniques for CMM calibration; measuring threaded holes using CMMs; standard validation procedures for CMM software; a configuration management strategy for packaging engineering (inspection) data into CAD systems; and a common database for storing and sharing engineering data throughout design, manufacturing, and inspection applications.

Lockheed Aeronautical Systems Company
Marietta, GA

The P-3 Orion maritime patrol aircraft and the C-130 transport are manufactured at this plant. Coordinate measuring machine technology is tightly integrated and used in all aspects of manufacturing. An engineer uses the CAD design to generate an inspection program in DMIS, an intermediate common language which allows down-loading of the program to an available,

appropriate CMM, regardless of CMM brand. A factor of 40 increase in inspection productivity is the result of this CAD integrated, networked inspection system!

Westinghouse Electric Corporation - Marine Division
Sunnyvale, California

The Marine Division of Westinghouse Electric Corporation primarily produces Trident missile launch systems, ship propulsion systems, and marine diesel engines. A missile launch system includes a barrel, barrel cap, and chambers for pressurized steam. A ship propulsion system includes a steam turbine (rotating turbine and stationary turbine), gears, gear casings, and a shaft. The tightest tolerance for gears is 5 micrometers for profile tolerance. A Hofler gear measuring machine is used to measure the gear surfaces for checking whether the gears meet the tolerance requirements. The Division is interested in the following capabilities to improve the utilization of CMMs: advanced tolerance verification algorithms, methods to determine the distribution of sample acquisition (uniform or algorithmic), soft functional gaging, inspection planning technology, the development and maintenance of inspection procedures for industry. Currently NAVAIR has these kinds of inspection procedures, used for checking machine tool performance using the B5.5 standard, measurement of gear tooth spacing along the pitch circle, and standard ways of calculating risks for both producers and consumers of CMM data.

Bell Helicopter TEXTRON
Fort Worth, Texas

Bell Helicopter produces H1W Cobra helicopters for the Marine Corps and V22 Osprey tilt-wing airplanes for the Navy. We visited two plants. Plant 1 has equipment and processes for machining, inspection, assembly, composite material processing, and helicopter testing. In the inspection facility, the measurement of blades, gears, and other mechanical parts is performed. Specialized measuring machines are used for gear teeth measurements. Helicopter blades are checked for surface cracks and defects using nondestructive testing methods. The forms of blades are measured using CMMs with touch-trigger probes which are used to collect measurements. Points to measure are determined by engineers in the Engineering Department. Gear manufacturing and measuring machines, and gear making processes are in Plant 5. The gear measurement laboratory, adjacent to the machine shop, uses Maag and Hofler machines for gear tooth measurement of gear teeth. The machines have probes to trace the gear teeth surfaces. The trace, which is the combination of the movement of the probe normal to the gear surface and paper, gets recorded on paper. The reading is in analog form. A plastic transparency with a cut of gear tolerance zone is put onto the trace. If any portion of the trace is out of the tolerance zone determined by overlaying the plastic transparency onto the analog reading on the paper, then the gear is considered out of tolerance. The out-of-tolerance gears will get either rejected of reworked depending on the material condition.

APPENDIX B

Aggregate Results of the Questionnaire for a Survey of Navy/DoD/Industrial Requirements in Dimensional Inspection

******NOTE******

The numbers listed before each item indicate the number of occurrences of each item as tallied from all the completed questionnaires.

I. What is your facility/company's profile?

Type of Business (check the most appropriate one):

1 OEM
4 Job-shop
3 Specialty Shop
4 Metrology Laboratory
0 Procurement Office
1 Standard Laboratory
0 Arsenal
1 Quality
2 Rework Center
2 Research Center
1 Incoming Inspection Laboratory
6 Navy Supplier
1 DoE agency
8 Others (specify)____________________

Type of product your company manufactures (check all that apply):

0 Dimensional Measurement Equipment
- *0* CMMs
- *0* Vision inspection systems
- *0* Mechanical probes
- *0* Measurement services
- *0* Others (specify)____________________

8 Aeronautic/Aerospace
0 Jet Engine
1 Automotive/Trucks
0 Automotive components
1 Electronics
0 Electrical goods
0 Computer hardware/software

0 Photo machines - camera/film/copier
3 Calibration Services
0 Standards
12 others (specify) Surface & sub-surface ship components and assemblies

Facility/Company Size:
Number of employees (check one):
4 1 - 49
2 50 - 99
5 100 - 499
4 500 - 999
7 1000 or more

II. What are the dimensional and shape characteristics of parts you deal with in your company?

Size ranges of manufactured parts (check all that apply):
2 less than 1 mm on a side
11 between 1 and 10 mm on a side
17 between 10 and 50 mm on a side
18 between 50 - 100 mm on a side
19 between 100 - 500 mm on a side
17 between 500 - 1000 mm on a side
18 greater than 1000 mm on a side

Types of geometric forms in the parts:
19 cylindrical
18 planar
14 parallelepiped
16 torus-shape
17 spherical
21 sculptured curve
20 sculptured surface
8 others (specify)

III. What are tolerance requirements on designed parts?

Tolerance ranges (please check appropriate ones):
2 less than 0.001 mm
6 0.001 - 0.009 mm
16 0.01 - 0.1 mm
19 greater than 0.1 mm

Tolerance types (please check appropriate ones):

20 geometric tolerances

18 plus-minus tolerances

  17 apply to length

  17 apply to angle

2 others (specify)________________________________

IV. What tolerance standards does your company use? (check all that are used)

ANSI standards

17 Y14.5

ISO standards

2 1101

0 286

0 8015

0 2692

0 5458

0 5459

other tolerancing standards (specify)

____

Please describe any areas in which the standards you use could be improved:

____

____

V. What dimensional measurement equipment do you use?

18 coordinate measuring machines (CMMs)

type of CMM

  9 manual

  11 semi-automatic (joystick control)

  13 DCC

sensors used on CMM

  15 mechanical probes

    14 touch-triggered

    10 scanning

    0 others (specify)________________________________

  3 laser

  0 video

  1 others (specify)________________________________

4 vision inspection systems

11 others (specify)________________________________

VI. How is the equipment you use calibrated ?

Frequency of calibration operation taken place:

0 less than once a day
0 less than once a week
4 less than once a month
10 less than once a half year
6 less than once a year
2 others (specify)

Is ANSI B89.1.12 applied ?

8 Yes
8 No

VII. Do perform interim test on your measurement equipment ?

12 Yes (specify)

8 No

VIII. Do you calibrate probes ?

Specify Methods:

How often:

IX. Is the measurement environment controlled?

15 Temperature
13 Humidity
1 others

Specify environmental control method if any:

X. How do you determine the sampling strategy? ______

______

______

______

XI. Which, if any, standards do you use for dimensional inspection?

5 ANSI B89.3.1
0 ANSI/ASQC E-2
3 ANSI/CAM-I DMIS
1 others (specify) ______

XII. Do you use CAD systems?

15 Yes
6 No

XIII. What CAD functions listed below do you use?

12 Drafting
12 Dimensioning parts
12 Tolerancing parts
11 3-D geometric modeling
8 IGES translation
8 CAD/CAM link

XIV. Do you use computer-aided inspection software?

9 Yes,
What kinds of function do you use?
3 inspection path generation/verification
5 DMIS program generation
Is there a CAD/CMM link?
4 DMIS
2 Vendor provided data format
11 No.

XV. What mathematical functions do you use for dimensional and tolerance verification?

19 Datum and datum reference frame establishment
18 Distance between two geometric entities
16 point to point
14 point to line
14 point to plane

14 line to line
14 line to plane
14 plane to plane
4 others (specify)________________

14 Size tolerances
- *6* Minimum circumscribed size
- *6* Maximum inscribed size
- *8* Least-squared size
- *1* others (specify)________________

17 Form tolerances
- *13* roundness (circularity)
- *11* straightness
- *10* flatness
- *12* cylindricity
- *1* others (specify)________________

14 Orientation tolerances
- *10* parallelism
- *10* angularity
- *10* perpendicularity
- *0* others (specify)________________

15 Position tolerances
  - *6* with material condition modifiers
  - *7* without material condition modifier
- *11* Concentricity
- *7* Coaxiality
- *6* Symmetry
- *0* others (specify)________________

17 Profile tolerances
- *12* Profile of a line (curve)
- *11* Profile of a surface
- *0* others (specify)________________

17 Runout
- *10* Total runout
- *11* Circular runout
- *3* others (specify)________________

4 Free state variation control

0 others (specify)

____

____

XVI. What measured data do you capture and how it is used?

Types of measured data:
19 measured sizes (diameter, length, etc.)
17 measured geometric tolerances
20 pass/fail
1 others (specify) ________________________

Types of usage:
9 process monitoring
8 process correction
16 manufactured part screening
10 statistical process control
6 others (specify) ________________________

XVII. What kinds of new technology (in dimensional inspection) you want to buy that are currently not available?

____

____

____

APPENDIX C
The NIST Study Team

David Stieren, Team Leader
Precision Engineering Division

David Stieren has a bachelor's degree in mechanical engineering from the Catholic University of America, and has completed the course work for a master's degree in technology management from the University of Maryland. He has over eight years of experience in dimensional metrology and CMM-related technologies while employed at NIST and the Navy Primary Standards Laboratory, East. He also has experience in DoD program and project management through a NIST detail to the Office of the Secretary of Defense ManTech Program Office. He has authored/co-authored several technical papers on various metrology and programmatic issues.

Ralph Veale
Precision Engineering Division

Ralph Veale is a graduate of Indiana State and Pennsylvania State Universities. He is the group leader of the Dimensional Metrology Section of the Precision Engineering Division at NIST. He has more than 35 years experience in dimensional metrology, with extensive experience in CMMs, a wide array of dimensional calibrations, and high precision measurement. He was a group winner of the IR-100 award in 1985 for the development of software correction algorithms to correct for CMM machine errors, and has authored/co-authored several technical papers related to dimensional metrology.

Dr. Howard Harary
Precision Engineering Division

Dr. Howard Harary is a Physicist in the Machine Metrology Group, Precision Engineering Division at NIST. He received his PhD from Harvard University and was a post-doctoral fellow at Yale University. Dr Harary has over eight years of research experience in the field of coordinate measuring machines, and has a special interest in probing technologies and strategies. Dr. Harary has authored/co-authored numerous technical papers and reports relating to his areas of expertise, especially relating to probing technologies.

Dr. Shaw C. Feng
Factory Automation Systems Division

Shaw C. Feng holds a Doctorate and Master's degree in Mechanical Engineering from the University of Wisconsin-Madison. He has worked with dimensional metrology as a software expert at NIST for over four years and has extensive experience in CAD/CAM systems and automated inspection systems. He also has extensive experience in dimensioning and tolerancing theories, methodology, interfacing standards, and data analysis algorithms. Dr. Feng has published many in-depth technical papers and reports related to the subjects of his expertise.